Deliverable 2.4 – Work Package 2: Control solutions for island operation and black start capabilities of OWPP

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Deliverable description

The main objective of this deliverable is to present the results related to the control solutions for black start capabilities from offshore wind farms. A brief summary is given in the following, with the detailed analysis, implementation and results being available in two scientific publications attached to this report.

High volume integration of RES into the power system makes it harder to maintain reliability and stability of power supply in the grid due to introduction of variable power flows and thus complicating grid operation. Moreover, the decrease in reactive power reserve due to replacement of conventional synchronous generation destabilizes the long-distance 25 transmission corridors between load-centres and large-scale RES, such as offshore wind farms (OWF), during system contingencies. Additionally, inertial decoupling from the grid by the power electronic converter (PEC) interface with over-burdened reserves results in decreased transient stability. This increases the risk of wide-area blackouts, especially in strongly linked networks.

Traditionally, blackstart (BS) service has been provided mainly by coal or gas-fired generators and pumped hydro storage due to their capability to meet all the technical requirements. However, as large conventional generation plants are being phased out in favour of renewables and non-traditional technologies the cost of blackstart services is increasing.

For complete power system restoration, three stages must be completed viz. the restoration of generation units, the transmission system, and the loads with the aim to minimize restoration time & maximize load picked-up at each moment. After the decision to implement BS-plan is taken, a set of defensive actions are carried out to save as many generation units as possible followed by a clearly defined plan with the target system-states and the steps to achieve them, to avoid re-blackout. These mainly inlcude the blackstart of BSUs, voltage propagation to crank-up non-BSUs (with islanding), energization of the bulk power transmission system, optimal load pick-up while maintaining system stability, and finally, meshing & island synchronization to enhance the resilience of the recovered network against contingencies, before connecting to the grid.

Taking inspiration from the grid-restoration procedure as described above, the OWPP-BS energization sequence can be separated into target states (for a schematic representation see Figure 1 in the attached P1):

1) Self-Start: The first step is the self-startup of the WT using an internal backup power supply for initial energization of its auxiliaries and yaw & pitch mechanisms, to start producing power from the wind, without depending on an external power supply.

2) Self-Sustain: Once the rotor is oriented to the wind direction, the WT can start rotating and producing energy to sustain itself, assuming steady high wind conditions. This requires the WT grid-side converter (GSC) to operate in a power-curtailed grid-forming mode for energizing the WT-transformer and supplying the auxiliaries & controls.

3) Parallel Operation: Once WTs can sustain themselves, the next stage requires synchronized parallel startup & operation of multiple PEC-interfaced WTs in a WPP as a voltage-controlled island, possibly adapting microgrid control strategies. During this stage, few BS-capable WTs can operate in grid forming mode, while others connect.

Blackstart and islanding operation requirements have been included as options for wind power plants (WPP) in the ENTSOE network codes, where the relevant TSO is allowed to request these functions to support grid-recovery. Driven by grid codes, state-of-the-art wind turbines (WT) are already capable of providing some services that are a part of the restoration process eg. frequency control (Fast Frequency Response) & voltage support (Low Voltage Ride Through, LVRT), and are expected to deliver more advanced requirements like Inertia Emulation, Power Oscillation Damping and Reactive Current Injection, which are increasingly being demanded by grid-codes.

A generalized structure of different grid-forming control strategies that can be applied for controlling wind turbines as voltage sources to enable the blackstart and islanding capabilities of OWPPs is presented. It then focuses on testing four different methods during the various stages of energization of an onshore block-load by an HVDC connected OWPP. The aim is to characterize the different techniques and compare their capability to deal with the transients in a controlled manner while maintaining stable voltage and frequency at the offshore terminal.

An overview of the different strategies for the participation of offshore wind in a traditional bottom-up power system restoration procedure is presented. The focus is on grid-forming as the main control change required to enable blackstart and islanding services from wind turbines, facilitate their earlier participation and minimize the dependence on auxiliary diesel generators. The overall structure of grid forming control has been explained with the constituent functional blocks, along with conceptual explanation of 4 different techniques viz. VSG, PSC, dPLL and DPC. These methods were then tested in a study of the blackstart of onshore load by an HVDC-connected offshore wind farm, focusing on transients due to energization of transformers, cables, MMC cells and HVDC link. The simulation results demonstrate that all the 4 methods are able to deal with the energization transients in a controlled manner while maintaining stability of voltage and frequency at the offshore terminal. However, differences in their transient behaviours were observed.

The details of the performed work are given in the attached papers:

P1: Jain, A., Das, K., Göksu, Ö., & Cutululis, N. A. (2018). Control Solutions for Blackstart Capability and Islanding Operation of Offshore Wind Power Plants. In *Proceedings of 17th wind Integration workshop* Energynautics GmbH. https://doi.org/10.5281/zenodo.3269542

P2: Jain, A., Sakamuri, J.N., & Cutululis, N. A. (2020). Grid-forming control strategies for blackstart by offshore wind farms. Submitted to *Wind Energy Science*

P1

Control Solutions for Blackstart Capability and Islanding Operation of Offshore Wind Power Plants

Control solutions for Blackstart capability and Islanding operation of Offshore wind power plants

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***Abstract*—**
Environmental sustainability concerns make renewable energy systems (RES) integrated into the grid crucial for future power systems. Amongst RES, wind energy especially offshore wind power plants (OWPP) show huge promise. Increasing penetration of RES requires re-thinking of critical operation states that could lead to an increased risk of generation tripping that ultimately triggers blackouts. Thus maintaining reliability, robustness and stability of grid operation has become more complex and so blackstart (BS) and islanded (Is) operation requirements are being considered as options for WPPs in the grid codes. Additionally, advanced control functionalities provided by modern wind turbines (WT) owing to their power electronics converter (PEC) interface, enables them to provide fast, high power environment-friendly BS capability that facilitates grid recovery & reduces the impact of a blackout. In this paper, the motivation for BS capabilities in OWPPs has been presented, and the different stages of restoration using OWPPs identified. Finally the existing control solutions and potential challenges for BS&Is using OWPPs have also been investigated.

I. Introduction

The rising demand for power necessitates an increase in the installed generation capacity. Moreover, sensitive and critical loads impose a need for higher reliability in grid operation. Thus environmental problems like global warming, sustainability concerns and energy security make renewable energy systems (RES) crucial for future power systems.

The European Union's (EU) 2009 directive on the promotion of the use of energy from renewable sources sets an overall goal across the EU for a 20% share of RES in the total energy consumption by 2020 [1]. The European Commission has now proposed a target of at least 27% renewables in the final energy consumption in the EU by 2030 to make the EU a global leader in renewable energy [2]. Along with the EU, other international players such as USA, China and India, are also setting out several energy strategies for a more secure, sustainable and low-carbon economy.

Amongst RES, wind energy is the fastest growing [3] due to its abundance and cleanliness [4], and shows huge promise for the future as the EU has decided to make wind power a major electricity source. In addition to quick growth in the total installed capacity, the size of the individual wind turbine (WT) is also increasing to achieve a lesser price per kilowatt hour [3]. Moreover, due to onshore space constraints, large offshore wind power plants with high power WTs have gained popularity and this has led to an increase in the share of offshore wind energy [4], [5].

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However, with increasing RES replacing conventional power plants, maintaining reliability, robustness and stability of grid operation, has become more complex due to the introduction of new, variable and more unpredictable power flows [6]–[8]. Morevoer, inertial decoupling of the rotating WT generator from the grid by the power-electronics converter (PEC) interface combined with the unpredictable line overloads caused by erroneous scheduling due to larger errors in forecasting over timescale of hours, leads to violent frequency-swings and over-burdened reserves, resulting in decreased transient stability [9]. All of the above factors can result in cascaded tripping of generation and potentially trigger blackouts, especially if a large generation is involved and thus future power systems operating with a large volume of RES might require black-start (BS) capabilities and controlled islanded operation (CIO) to support the transmission system operator (TSO) in the event of a blackout to restore the power system [3], [6], [9]–[11].

The next section of this paper presents the main factors motivating the need for development of blackstart and islanding (BS&Is) capabilities in offshore wind power plants (OWPPs).

II. Motivation

The recent increase in the integration of RES like large OWPPs far from load-centres, has increased the transnational power exchanges and led to the system being operated closer to its limits due to constraints on expansion of transmission-assets [8]. Moreveor the shift towards PEC-interfaced controllable RES is causing the system dynamics to change which poses a risk to the power system dynamic stability [8], [9]. Furthermore, the stronger linking of the national power systems, in combination with the previous factors, has translated into an increased risk of wide area blackouts [8]. Thus, with the growing proportion of wind power in the grid, more advanced grid requirements like BS, usually targeted to large thermal power plants, can be addressed by the large OWPPs that are integrated through voltage source converter (VSC) based high voltage direct current (HVDC) transmission [3]. Additionally, due to absence of near-shore wake effects, large OWPPs with cable distances of 100 km or more have steadier wind conditions compared to onshore/near-shore OWPPs that typically have higher availability uncertainty.

During the power system restoration process after a blackout, plants with black-start units (BSU), usually pump-storage hydro power plants or small gas turbines, energize a network island and generate initial voltage for supplying auxiliary power to start larger conventional thermal power plants [12]. However, this is characterized by long start-up times. In contrast, large VSC-HVDC connected OWPPs, far from the shore and composed of state-of-the-art WTs, can provide fast & fully-controlled [4], [6], [7], high-power environment-friendly BS capability with high availability [3], [12], [13]. Thus BS&Is operation requirements have been included as options for WPPs in the ENTSO-E network codes, where the relevant TSO is allowed to request these functions to support grid-recovery [4], [13].

The strategies for optimal power system restoration plans after a complete blackout are highly dependent on the location and characteristics of BSUs in the power grid such as survival & startup power, capacity, prime-mover's frequency response etc., and also the network topology of the grid under consideration [14], [15]. Since the restoration duration reduces exponentially with the availability of initial sources of power (BSUs) [16], having BS capability in OWPPs could significantly reduce the extent, intensity & duration, and thus the overall impact [16] of blackout events. Wind power integrated in the system has already been shown to improve the restoration time and reduce the unserved load energy during the restoration period [17].

Traditionally, during restoration after a blackout, the main onshore-grid is used to power the OWPP via the VSC-HVDC link in which the offshore-VSC, shown in Fig. 1, is controlled in *grid forming* [18] mode and the WTs connect as *grid following* [18] units [17]. Most WTs normally start automatically about 10 minutes after getting a stable voltage following a blackout, which encourages the TSO to include them earlier in the restoration process to participate in charging the HVDC-link and contributing in a faster load pick-up by fast ramp-up [17]. However, at the beginning of the BS-restoration process, the network is not completed and the grid is not strong enough to allow large OWPP restoration as that may lead to a second blackout [17]. Thus, OWPPs equipped with *grid forming* capabilities will not only not have to wait for completion of the network reconstruction, but can also do *controlled islanded operation* to ensure the continuity of power supply [11] and participate in sectionalizing strategy [19] for defense against blackout. This facilitates *bottom-up* grid-recovery (build-up or parallel power system restoration) that reduces restoration time & the unserved load compared to a *top-down* (build-down) approach [19], [20].

Additionally, frequency and voltage support functionalities of VSCs such as dynamic reactive power control for improved voltage stability, inertia emulation, self-commutation, indefinite operation at very-low power transfers, under-voltage ride-through etc. [21] can also be provided by the modern WT's state-of-art PEC-interface [3], [6], [9], [12], enabling them to be controlled as *offshore grid-forming* units. Self-starting WTs that can produce power to sustain themselves, can avoid the risk to their health (moisture damage, icing up of electronics & equipment, bearing deformation and vibrations due to unfavourable yaw-axis orientation) as long as there is wind, especially when off-line for long durations due to a transmission line outage or a regional black-out and thus minimize or totally avoid the use of the backup diesel generator [13]. BS-capable OWPPs also help minimize the use of the offshore-substation diesel generator backup-power for supplying the auxiliaries (controls, switchgear, climate units for VSC maintenance, station start-up) & forming the collector-grid [13]. Since presence of diesel generator increases the insurance & maintenance cost considerably, BS&Is capabilties in WTs would be a preferable economic solution.

Moreover, *offshore grid forming* WTs allow diode rectifier unit (DRU) [22]–[24] or thyristor-based line commutated converter (LCC) with reduced filter size [25], that are preferred at higher power levels, to be used in place of the offshore-VSC although it allows more controllability & flexibility. This reduces installation & operational costs, and increases efficiency, system reliability and robustness [22]–[24].

III. Control Solution

This section begins with a brief description of the target states and the major/significant technical challenges in the proposed OWPP BS-energization sequence followed by the control strategies required for BS&Is capabilities in OWPPs.

A. Target States

For complete power system restoration, three stages must be completed viz. the *restoration* of generation units, the transmission system, and the loads with the aim to minimize restoration time & maximize load picked-up at each moment [17]. After the *decision* to implement BS-plan is taken, a set of *defensive* actions are carried out to save as many generation units as possible followed by a clearly defined plan with the *target system-states* and the steps to achieve them, to avoid re-blackout. These mainly inlcude the *blackstart* of BSUs, *voltage propagation* to crank-up non-BSUs (with islanding), *energization* of the bulk power transmission system, optimal *load pick-up* while maintaining system stability, and finally, *meshing* & *island synchronization* to enhance the resilience of the recovered network against contingencies, before connecting to the grid [11], [14], [16], [19].

Taking inspiration from the grid-restoration procedure as described above, the OWPP-BS energization sequence can be separated into *target states* [21] presented below with a schematic explanation in Fig. 1.

1) Self-Start: The first step is the *self-startup* of the WT using an internal backup power supply for initial energization of its auxiliaries and yaw & pitch mechanisms, to start producing power from the wind, without depending on an external power supply [13].

2) Self-Sustain: Once the rotor is oriented to the wind direction, the WT can start rotating and producing energy to sustain itself, assuming steady high wind conditions. This requires the WT grid-side converter (GSC) to operate in a *power-curtailed* [13] *grid-forming* [18] mode for energizing the WT-transformer and supplying the auxiliaries & controls.

3) Parallel Operation: Once WTs can sustain themselves, the next stage requires *synchronized parallel* startup & operation of multiple PEC-interfaced WTs in a WPP [13], as a *voltage-controlled* island, possibly adapting microgrid control strategies [26]. During this stage, few BS-capable WTs can operate in grid forming mode, while others connect

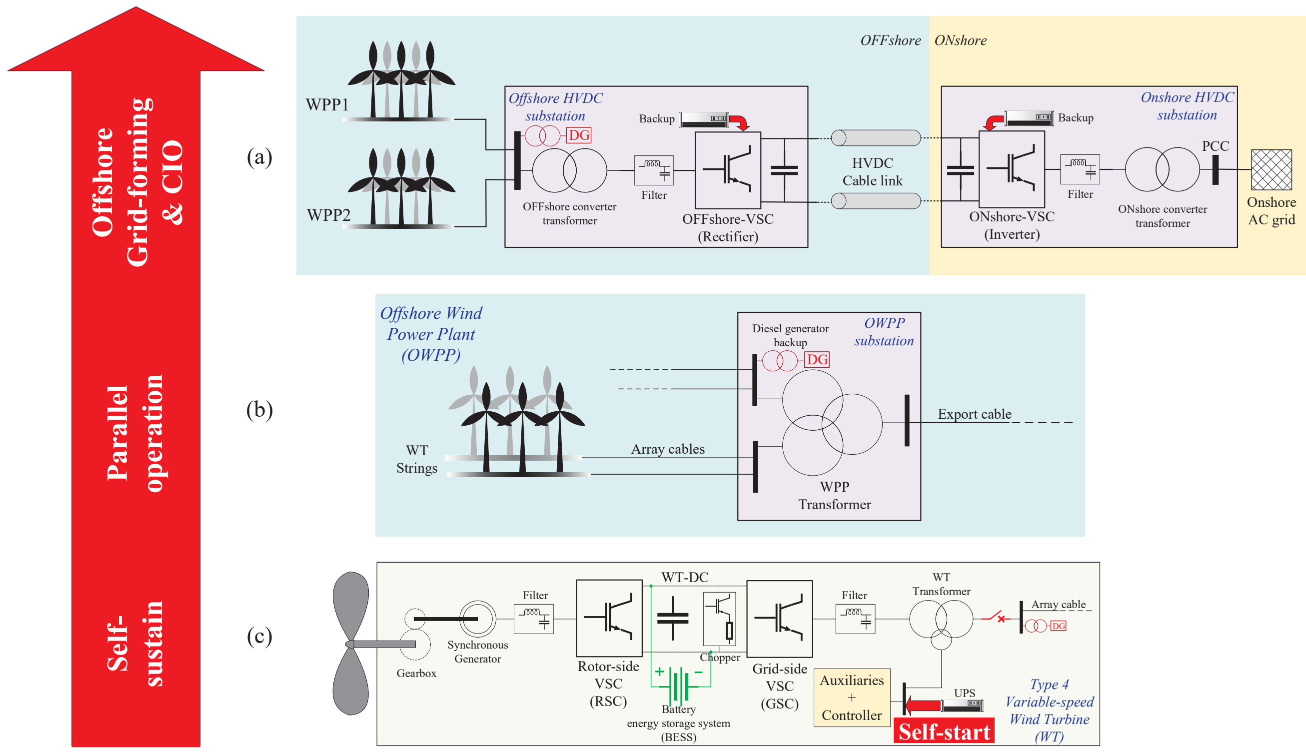

Fig. 1. Energisation sequence for blackstart restoration using offshore wind power plants (OWPP), with schematic diagrams of (a) VSC-HVDC connected OWPP-cluster (b) offshore wind power plant (c) full-scale power-electronics interfaced wind turbine

in grid-following mode to ensure effective & stable islanded operation followed by parallel power system restoration for increased voltage-stiffness [27]. The energy extracted from wind is then used to energize the array cables and the WPP-transformer, to prepare for the next stage.

4) Offshore Grid Forming: With the ultimate aim being connection of the OWPP to the main onshore grid to facilitate restoration and block-load recovery, the next stage consists of *coordinated parallel operation* of multiple WPPs in a cluster to form the isolated offshore collector-grid in a controlled manner [12]. This is required to effectively emulate stiff voltage source behaviour for charging the export cables & energizing the converter-transformers, while sharing the WPP-substation auxiliary loads, followed by VSC & HVDC-link energization.

5) Controlled Islanded Operation (CIO): Finally, it is necessary to ensure the stability & robustness of the islanded operation of the OWPP and the offshore grid. The objective of this stage is thus to maintain voltage & frequency stability especially during large load-pickups & WT-connetion/disconnection transients, along with robustness to different fault-scenarios (in offshore & DC grids), harmonic instabilities due to the PEC-interface [28] and HVDC-link resonance issues [29]. Once stable CIO of the OWPP is guaranteed, connection to the main onshore-grid can be done.

B. Challenges

Most modern WTs can do *self-startup* using the on-board (internal) UPS [13], [23], and already include some kind of local energy storage for control & measurement equipment power-up, emergency braking, and yaw & pitch actuation.

After start-up, the challenge is to energize the WT-DC link for VSC-operation and then generate a stiff voltage, to energize the WT-transformer & deal with the magnetic inrush currents by controlling the WT-GSC with support from local energy storage or the backup supply, if required. Moreover, the WT output power should be limited (*power-curtailment* at high wind) to prevent rotor-overspeeding, because the load is not sufficiently large to consume the additional active power [13], [30].

The next major obstacle is to operate several WTs in harmony to control the steady-state & transient voltage issues such as over-voltage & harmonic distortions due to the magnetic inrush currents of WPP-transformer energization and the initial charging currents of long unloaded-array cables, that impose demands on reactive power capability of the WTs [11], [15], [16]. At the same time, the PEC control should deal with WT-connection/disconnection switching transients, harmonic instabilities & non-linear load sharing, while managing the on-line WTs in a *coordinated parallel-operation*.

Morevoer, a weak offshore grid and the highly non-linear loading due to energization of long export cables, filter banks & HV-transformers [31] poses a risk of operation of protection devices that can trigger re-blackout. Thus well-planned and clearly defined guidelines for energisation of the network are needed. Additionally, a large number of WTs need to be operative in STATCOM mode to provide the reactive power required during the starting transients by the LCC/DRU, if used in place of the offshore-VSC [23].

Finally, the biggest constraint faced by WPPs being used for BS is the inherent fluctuating nature of the wind energy resource leading to a high availability uncertainty, for which energy-storage support along with down-regulated/de-loaded operation is required [11].

C. Control Strategies

Independent active (P) & reactive (Q/VAR) power control, effectively current (I) control, along with direct voltage (V) & frequency (f) control is necessary for BS&Is capabilities in OWPPs [6]. This section gives a brief overview of the relevant control strategies existing in literature, that can be used for the BS-energization sequence using OWPPs, as shown in Fig. 1.

1) Self-Start & Self-Sustain: Currently, WTs rely on an on-board power supply (UPS) for powering their controllers for small durations [13], [23], but require a larger energy storage, connected at the WT-DC link [11], [32], for the initial energization of the yaw & pitch mechanisms to be able to continue producing power with the WT's own auxiliary loads (1-5% of rated capacity) as the only consumption. The *idling* & *power-curtailing* modes can be used for supplying the low power internal auxiliaries and charging the DC link. Additionally, the WT must manage the production of the minimum and fluctuating power due to fluctuations in its own loads and varying wind speeds [13].

2) Grid Forming: Unlike the traditional LCC-HVDC system, the VSC-HVDC system does not require generation capabilities at both ends of the link for operation, which allows *top-down* restoration of remote OWPPs/islanded grids after a transmission power outage, by importing power from the healthy onshore-grid [4], [7], [33] and operating the offshore-VSC in *grid forming* [18] mode while the WTs connect in *grid-following* [18] mode [11], [13]. However, by controlling the WTs as a voltage source powered by the wind, it is possible to form the *islanded* offshore collector-grid in a controlled manner [12] without dependence on external grid-forming units, and thus, facilitate *bottom-up* restoration of the onshore-grid using BS-capability of OWPP. WTs equipped with grid-forming capabilities also enable *offshore* HVDC-rectifier energization as opposed to the conventional *onshore* HVDC-inverter energization [10], [23].

During grid-connected operation, the onshore-VSC is operated in *grid-following/supporting* mode [18], which requires an active onshore grid to which the VSC can synchronize [10], [12]. However, during BS conditions, the AC network is passive as no generation is connected, so the VSC must effectively operate as a UPS in *phasor-control* or *synchronous-machine emulating* mode to control the AC-V (amplitude & phase) and f [21]. This control mode is also used for operation with a very weak AC network connection, isolated wind parks, and during quasi-islanded or islanded conditions with relatively little or no generation online [21].

For BS-capability in OWPPs, the WT-RSC controls the WT-DC link voltage so that the WT-GSC can be controlled as a voltage source to control the offshore AC-V & f. The offshore-VSC (rectifier) then controls the HVDC-link voltage [10] while the onshore-VSC (inverter) controls the P, Q injected into the main onshore-grid, when connected. However, when a DRU replaces the offshore-VSC, the HVDC-link voltage is controlled by the onshore-VSC [31]. A distributed V, f control is presented in [22]–[24] for grid-forming operation of WT-GSC, especially in islanded mode when the main grid is not available.

To avoid dynamic issues associated with V-control, the WT must be controlled to absorb the generated VAR when energizing the unloaded lines [11], [16] and do gradual buildup of the AC-V to minimize the transformer in-rush current [21]. The PEC-interfaced WT can provide Q-compensation during steady-state, dynamic and transient conditions to support the power system restoration procedure, behaving in a way similar to a STATCOM [34], [35]. Moreover, the length of line energized & the size of transfomers needs to be considered to optimize the restoration process as energizing a small section prolongs it while a large-section risks damage to the equipment insulation. Finally, coordination between the HVDC link start-up and the restored AC system strength is necessary as a certain strength of the AC transmission system is required to absorb the startup impact of the HVDC link, else the system can collapse or even suffer re-blackout [36].

3) Parallel Operation: Control strategies developed for microgrids can easily be extended to the case of large OWPPs, taking into account their specific system characteristics [22]. In microgrid islanded operation, VSCs are responsible for f-control & V-regulation. *Single*-master operation (SMO) or *Multi*-master operation (MMO) [27] with a *3-level hierarchical*-control structure [26], can be used to coordinate multiple WTs in a WPP on the lower level and multiple WPPs in a cluster on a higher level, to emulate a *stiff & controlled* voltage source.

The lowest *inner* level consists of the inner V/I-control loops to emulate V/I-source behaviour of the VSC and provide maximum power point tracking, power limitation, fault ride-through and power-quality enhancement capabilities [26]. The next *primary* level consists of the *droop*-control to mimic synchronous generator behaviour, add synthetic inertia & avoid large circulating currents between paralleled PEC-based sources, without using any critical communication [26]. Although this scheme provides high reliability & flexibility, it also has several drawbacks such as power sharing transients due to output impedance, non-linear load sharing issues, load-dependent f-deviation and inherent tradeoff between P/Q-sharing & V/f-regulation [26].

Thus, *secondary* & *tertiary* control levels along with *harmonic* current-sharing techniques are required to restore the deviations produced by the virtual-inertias & output-impedances and avoid circulating distortion powers [26]. Additionally the *virtual-impedance* loop helps control the output impedance and allows intelligent transition between V-control & PQ-control modes of VSCs, which helps take advantage of fast VSC-operation while avoiding large transients due to smaller output impedance [20], [27]. The *secondary* & *tertiary* levels also provide grid-synchronisation control, low-voltage ride-through and help improve power quality & V-stability at the point of common coupling (PCC) with the onshore-grid [26]. Moreover, droop-control independent of the offshore-grid characteristics, obtained by using the WT-RSC to control WT-DC link voltage, can provide robustness to set-point changes, dynamic voltage-issues and connection-disconnection transients during BS-energization [22].

It is also beneficial to have a *sectionalizing strategy* to pre-plan the WT-islands in the OWPP during the energization & synchronization process, based on conditions such as BS-availability & capability, generation-load matching, grid-forming capabilities with load-pickup etc., to use the OWPP optimally for parallel power system restoration (build-up) [19], [37].

4) Controlled Islanding: Networks with a large number of PEC-interfaced units face many challenges to maintain stability [38] due to *harmonic-instabilities* [28] and substantial *network-configuration changes* [20] from moderately strong AC to weak & extremely-weak AC, islanded & passive networks.

The wide timescale control dynamics of VSCs can result in cross couplings between the electromechanical dynamics of electrical machines and the electromagnetic transients of power networks, which may lead to oscillations/*harmonic-instabilities* (due to negative damping of the control output admittance) across a wide frequency range, depending on both the specific controllers of the converters and the power system conditions [28].

When moving to islanded operation or when a large load is connected during islanded operation, the initial high imbalance between local load & generation may lead to large f-deviations & transient overloads. However, due to economic reasons, VSC overload capacity is limited and thus intelligent control is required to mitigate the transients and maintain stability [38]. Thus, during restoration, the allowable size of load pick-up should be lesser than the rate of response of prime movers already on line [16] to keep the f within acceptable limits, and a minimum load pick-up time interval should be ensured to allow the system to come back to a stable operation state. A *coordinated virtual-inertia* based control strategy has been proposed in [30] to utilize the WT to maintain the the isolated system-f, and thus enhance the f-stability during power system restoration. Additionally, most studies on VSC-HVDC control strategies are based on ideal conditions with balanced AC-V and so it is necessary to improve the VSC-HVDC system performance when WPP-V is unbalanced since faults are inevitable.

Trajectories of the system eigen-values and the load step-sizes can be used to assess the stability of the target states, and the position of the largest eigenvalue gives a measure of the stability margin of the system [39]. *Input-admittance matrix* or *impedance-based* system modelling can be used for stability analysis with generality [40] and stability can be guaranteed by making sure that the VSC dissipates power (non-negative conductance) at critical frequencies, particularly poorly damped resonances [41].

Finally, since WTs use wind as the resource for power production, they have an inherent variability and availability-uncertainty that lead to inherent reliability issues, although the variability decreases over a larger area and the availability-uncertainty, farther from the shore. Thus, energy storage can help improve reliability without having to increase spinning reserves [21]. Moreover, a *capability assessment* is needed to help ensure steady power production, strong grid-forming and stable islanded operation by the OWPP for supporting the TSO in the upstream onshore-grid BS-process. Thus, ultimately it is important to assess the variation of V-stiffness with weather fluctuations.

IV. Conclusion

The factors discussed in the motivation section show that equipping OWPPs with BS&Is capabilities is beneficial for improving the operational reliability, stability and security of the future power system with a large volume of RES. An energization sequence to achieve BS-restoration using OWPPs has been proposed in this paper, along with the major technical challenges faced during the different intermediate target stages. Finally, the control strategies for *grid-forming*, *parallel-operation* and *controlled-islanding* of WTs in OWPPs have been presented. These allow the OWPPs to be used as BS-units and facilitate grid-restoration after a blackout, thus helping minimize the restoration time & the unserved load.

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P2

Grid-forming control strategies for blackstart by offshore wind farms

Grid-forming control strategies for blackstart by offshore wind farms

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Abstract. Large-scale integration of renewable energy sources with power-electronic converters is pushing the power system closer to its dynamic stability limit. This has increased the risk of wide-area blackouts. Thus, the changing generation profile in the power system necessitates the use of alternate sources of energy such as wind power plants, to provide blackstart services in the future. This however, requires *grid-forming* and not the traditionally prevalent *grid-following* wind turbines. In this paper, four different grid-forming control strategies have been implemented in an HVDC-connected wind farm. A simulation study has been carried out to test the different control schemes for the different stages of energization of onshore load by the wind farm. Their transient behaviour during transformer inrush, converter pre-charge and de-blocking, and onshore block-load pickup, has been compared to demonstrate the blackstart capabilities of grid-forming wind power plants for early participation in power system restoration.

1 Nomenclature

AB	Auxiliary Breaker
AVC	AC Voltage Control
AVR	Automatic Voltage Regulator
BS	Black Start
BSU	Black Start Unit
CLC	Current Limitation Control
DPC	Direct Power Control
dPLL	Distributed PLL-based (control)
DR	Diode Rectifier
ESS	Energy Storage System
GSC	Grid Side Converter
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current

LVRT	Low Voltage Ride Through
MB	Main Breaker
MMC	Modular Multi-level Converter
OWF	Offshore Wind Farm
PCC	Point of Common Coupling
PEC	Power Electronic Converter
PIR	Pre Insertion Resistor
PIT	Pre Insertion Time
PLL	Phase Locked Loop
PSC	Power Synchronization Control
PSL	Power Synchronization Loop
RES	Renewable Energy System
RHP	Right Half Plane
RSC	Rotor Side Converter
SG	Synchronous Generator
SM	Synchronous Machine
SVG	Synchronous Var Generator
TOV	Temporary Over Voltage
TSO	Transmission System Operator
VSC	Voltage Source Converter
VSG	Virtual Synchronous Generator (control)
WPP	Wind Power Plant
WT	Wind Turbine
WT-DC	Wind Turbine (PEC-interface) DC link

2 Introduction

Environmental problems like global warming, coupled with increasing fuel prices and the global drive towards sustainable development & energy security, has accelerated the integration of renewable energy sources (RES) into power systems all around the world. Many countries have set out several energy strategies for a more secure, sustainable and low-carbon economy like the European Union's (EU) 2018 directive on the promotion of the use of energy from renewable sources (RED II) that sets an overall goal across the EU for a 32% share of RES in the total energy consumption by 2030. Such aims and measures to also exploit the potential of RES in transport and district-heating & cooling sectors, shows huge promise for electricity as the *fuel* of the future. Among the different RES, wind energy has seen a rapid growth in the installed capacity worldwide, from about 6.1 GW in 1996 to about 591.5 GW in 2018 (Tavner, 2012) and shows a huge promise for the future to be a major electricity source.

High volume integration of RES into the power system makes it harder to maintain reliability and stability of power supply in the grid due to introduction of variable power flows and thus complicating grid operation (De Boeck et al., 2016). Moreover, the decrease in reactive power reserve due to replacement of conventional synchronous generation destabilizes the long-distance transmission corridors between load-centres and large-scale RES, such as offshore wind farms (OWF), during system contingencies (Sarkar et al., 2018). Additionally, inertial decoupling from the grid by the power electronic converter (PEC) interface with over-burdened reserves results in decreased transient stability. This increases the risk of wide-area blackouts, especially in strongly linked networks (De Boeck et al., 2016). For example, as per the report by Australian Energy Market Operator, the failure of wind farm owners to comply with performance requirements to ride through major disruptions and disturbances led to blackout of the South Australia system in 2017, that affected about 850,000 people causing disruption to households, businesses, transport & community services, and major industries. Another very recent case is the unexpected reduction of 737 MW from Hornsea 1 OWF in the UK, that is cited to be one of the main causes of the system failure in August 2019 affecting about 1 million customers and causing travel chaos in and around London, according to the technical report by National Grid (2019a).

2.1 The changing paradigm

Traditionally, blackstart (BS) service has been provided mainly by coal or gas-fired generators and pumped hydro storage due to their capability to meet all the technical requirements (Elia, 2018; National Grid, 2019b). However, due to the previously mentioned decarbonisation aims, rising fuel costs coupled with ageing assets and reducing load factors, large conventional generation plants are being phased out in favour of renewables and non-traditional technologies which increases the cost of *warming-up* large generators and thus blackstart services (National Grid, 2019b). Since maintaining the status quo for blackstart & restoration is not an option, considerable changes are required to facilitate the participation of alternate sources like RES and non-traditional technologies in the BS-market given the modern evolving energy landscape. According to Elia (2018), there is a potential to open up the delivery of BS-service to aggregation of units (combined services) including variable generation (like wind, solar-PV), especially with support from energy storage systems (ESS). National Grid has also recently confirmed that combined services, interconnectors and sites with trip to houseload can also potentially provide BS-services.

Blackstart and islanding operation requirements have been included as options for wind power plants (WPP) in the ENTSO-E network codes, where the relevant TSO is allowed to request these functions to support grid-recovery (Göksu et al., 2017). Driven by grid codes, state-of-the-art wind turbines (WT) are already capable of providing *some* services that are a part of the restoration process eg. frequency control (Fast Frequency Response) & voltage support (Low Voltage Ride Through, LVRT), and are expected to deliver more advanced requirements like Inertia Emulation, Power Oscillation Damping and Reactive Current Injection, which are increasingly being demanded by grid-codes (Jain et al., 2019). This is possible due to the advanced functionalities of the full-scale PEC interface of modern WTs, mentioned in Chen et al. (2009), like improved

LVRT, self-commutation capabilities and independent control of active P & reactive Q/(Var) power. Seca et al. (2013) show that WTs owing to their fast start-up/ramp-up times, can be included earlier in the restoration process to provide Var-support and pickup load, thus decreasing the impact of a blackout event by reducing the restoration time & unserved load. However, connection of the currently prevalent *grid-following* WTs in the beginning of the restoration procedure can cause a recurrence of blackout as the grid connection is generally not stable enough (El-Zonkoly, 2015).

2.2 Wind for blackstart

Large OWFs can provide fast & fully-controlled, high-power, emission-free *green* blackstart services but there exists a gap between the present grid-code BS-requirements and current WT BS-capabilities as identified by Jain et al. (2019). Technological changes are neeeded to make WTs *BS-ready/BS-able* and the technical challenges associated with the different stages of energisation of an HVDC-connected OWF, along with control techniques to mitigate those issues have been discussed by Jain et al. (2018). A recent report by National Grid (2019b) also summarises the technological capability of non-traditional technologies like renewables & distributed energy sources to provide blackstart & restoration services. As regards wind power, large OWFs with full-scale converters and connected at the transmission level have the potential to meet the huge Var-requirements of network energisation (mainly long cables & lines), withstand transformer inrush transients, and cater to block loading, *provided* sufficient wind is available *and* controllers are adapted for blackstart. This makes HVDC transmission preferable for future OWFs due to the large charging Var required for long distance HVAC cables (Erlich et al., 2013).

The current turbine & converter controls are designed assuming a strong grid connection point which means that the grid-side converter (GSC) of the WT latches onto a pre-existing voltage signal provided by the onshore grid in case of an AC-connected OWF, or produced by the offshore HVDC converter operating in voltage-frequency control mode in case of HVDC-connected OWF (Bahrman and Bjorklund, 2014). However, to allow outward-energisation of the network of inter-array cables & transformers, create a power island that can supply local loads and energize the HVDC link converters & export cable with the ultimate aim to supply onshore block load, the WT should be able to produce its own voltage signal. This requires grid-*forming*, traditionally referred to as *voltage*-injecting control, as opposed to the conventional grid-*following* or *current*-injecting control. The two control philosophies are very well explained by (Rocabert et al., 2012). Voltage-injecting control concepts have been shown to deliver a superior performance compared to their current-injecting counterparts in system-split scenarios as demonstrated by Heising et al. (2019). Erlich et al. (2017) also shows that the temporary over-voltages (TOV) following islanding due to transformer-cable interaction can be avoided. Moreover, grid-forming WTs can also minimize the use of diesel generators that are currently employed to supply backup auxiliary power required for energization. Although, most modern WTs have an on-board UPS to power communications, protection & control for few hours during emergency shutdown (Göksu et al., 2017), a larger internal backup supply would be required for self-starting the WT for blackstart, especially after extended shutdown periods.

2.2.1 Hybrid

Traditional current-controlled WTs can be used with an external power supply (eg. diesel generator/energy storage) and a Synchronous Var Generator (SVG) or STATCOM, combining services into a joint *hybrid* blackstart unit (BSU) to facilitate WT participation in BS procedure as proposed in Aktarujjaman et al. (2006). The external supply provides startup power and sets the reference voltage & frequency for the isolated system, the SVG/STATCOM supports the Var requirement of the cables & transformers and stabilizes the voltage, after which the WTs connect to meet the load power demand. Zhu et al. (2018) shows that earlier participation of WT in the restoration procedure is feasible as grid-forming control allows blackstart & stand-alone island operation with better inherent *synchronous-machine like* inertial response during a transient, that can help absorb the initial impact of energization and ensure smooth load pickup, thus mitigating large voltage/frequency excursions that might occur during restoration. However, only the transients during load pickup and re-synchronisation to the grid have been studied, while energization of collector lines, export cables & transformers, that cause more transient stability challenges during energization, are not shown. Additionally, the major energization transients are taken by the ESS & SVG, while the WTs behave as *passive* power-sources to meet load-demand during the last stages of restoration.

2.2.2 HVAC

Recent studies by Martínez-Turégano et al. (2018) and Aten et al. (2019) demonstrate the potential capability of HVAC-connected OWFs to blackstart onshore grid using grid-forming controls in less than 25% WTs *and* assuming adequate wind resource. The results show that it is possible to do *sequential* energization of the array-cables & WT transformers, starting with one WT energizing its string followed by others synchronizing to it and then sharing the control of voltage & frequency. Shorter cable sections are energized first until enough WTs are connected to absorb the Var generated by subsequent cable sections. However, according to Elia (2018) & National Grid (2019b), a large gap to bridge is the energization of the export link while meeting grid code requirements.

2.2.3 HVDC

HVDC with Voltage Source Converters (VSC) can also be used as a standby facility for blackstart and restoration of the onshore AC grid, as demonstrated by the excellent voltage and frequency control performance in real system tests done by Jiang-Hafner et al. (2008), proving for the first time that VSC-HVDC helps reduce restoration time while facilitating a safer & smoother restoration process with lower investment & maintenance cost. With HVDC transmission gaining momentum as the preferred choice for longer distance connections to larger OWFs, Sørensen et al. (2019) show that the Skagerrak-4 (SK4) VSC-HVDC link between Norway & Denmark (DK) can be successfully used to ramp-up the voltage of an islanded 400 kV & 150 kV DK-network to energize overhead transmission lines, transformers and block load, followed by synchronisation to continental EU. Additionally, a *top-down* restoration test of the NEMO link between Belgium & the UK also demonstrates the capability of the VSC-HVDC interconnector to energize a *dead* Belgian grid from the *live* UK side (Schyvens, 2019). However, a diesel generator was used to provide auxiliary power for the *dead*-side converter. Simulation results by Becker et al. (2017)

show, without any details of the transformer/cable energization transients, that a VSC-HVDC connected OWF can respond to onshore load changes and participate in load restoration. Cai et al. (2017) analyzes the inrush current of transformers and cables (HVAC/HVDC) using EMT simulations, but with a diesel generator to pre-charge the offshore converter that then energizes the offshore collector grid, and the onshore converter pre-charged from onshore AC-grid, contrary to what is expected from an OWF to provide blackstart service. Simulation results presented by Sakamuri et al. (2019) demonstrate, for the first time, an HVDC-connected OWF with grid-forming control, sequentially energizing the offshore AC network including transformer, cables & converter through a pre-insertion resistor, followed by HVDC link energization and onshore converter pre-charging & de-blocking for picking up block load, successfully participating in restoration as a BSU. However, the energy imbalance in the HVDC link during the *DC-side* uncontrolled pre-charging of the onshore converter leads to a significant dip in HVDC voltage and large transients in the offshore & onshore converter cell voltages & valve currents. Grid-forming control, in addition to enabling blackstart and islanding capabilities of WTs, can also allow the use of *Hybrid*-HVDC connection with a diode rectifier unit (DRU) instead of the offshore VSC. The application of controls proposed in Blasco-Gimenez et al. (2010) for an OWF to ramp up the offshore AC grid voltage & control frequency, considering it as an inverter-based microgrid, has shown improved steady-state regulation during islanding when the DR-HVDC is not conducting, and smooth transition to current-control during grid-connected operation. This significantly reduces the cost-vs-performance, due to lower losses, especially for higher power levels, and lesser capital cost, along with increasing efficiency & reliability due to a lower probability of commutation failure than a VSC (Andersen and Xu, 2004).

2.3

This paper attempts to provide a generalized structure of different grid-forming control strategies that can be applied for controlling wind turbines as voltage sources to enable the blackstart and islanding capabilities of offshore wind farms. It then focuses on testing four different methods during the various stages of energization of an onshore block-load by an HVDC-connected OWF. The aim is to characterize the different techniques and compare their capability to deal with the transients in a controlled manner while maintaining stable voltage and frequency at the offshore terminal.

3 Grid Forming

Grid forming control of power electronic converters has been well studied for microgrids, where the role of PECs is to act as an interface between the small-scale distributed/renewable power generation units and the consumption points, leading to intertial decoupling of the rotating machines and making the microgrid system susceptible to oscillations caused by network disturbances. Grid forming allows a PEC to mimic Synchronous Generators (SG) for droop-based load-sharing, *synthetic* inertial-emulation, synchronized & stand-alone operation and blackstart behaviour, ensuring voltage and frequency stablility in *low-inertia* microgrids during varying loads, network disturbances and system configurational changes (islanding $\Longleftrightarrow$ grid-connected) (Tayyebi et al., 2018).

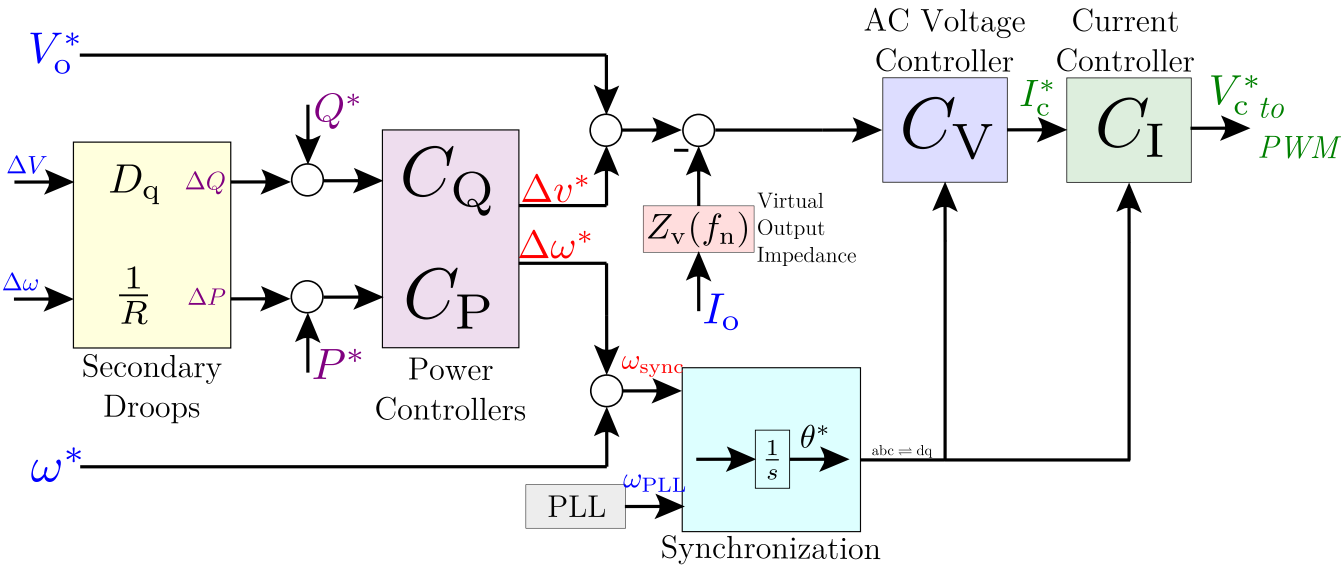

Figure 1. Grid forming control structure consisting of: inner current control loop C_{I}, the main AC voltage controller C_{V}, outer real & reactive power control loops $C_{\mathrm{P,Q}}$ and secondary droops (eg. virtual governor $\frac{1}{R}$ & virtual AVR D_{q}). Harmonic dependent virtual output impedance $Z_{\mathrm{v}}(f_{\mathrm{n}})$ can also be added.

An OWF is like a microgrid rich in power electronics although very different in that the voltage and power levels are much higher. Moreover, wind farm operators maintain a large amount ($>$100s) of WT-assets that are located very far from each other. Current sharing techniques for low rated inverters like the centralized controllers and the master-slave approach can be used only for paralleled systems that are close to each other and interconnected through high-bandwidth communication channels (Rocabert et al., 2012). These communication-based solutions can *not* be used for microgrids spread across several kilometres, as ensuring globally available, bidirectional, reliable & robust, low-power secure communication architecture becomes increasingly costly. Moreover, larger communication links increase delays which is undesirable in cases where a fast high-bandwidth link is required. This gave way to *droop control* algorithms with a *hierarchical* structure being used in microgrids, especially for islanded operation of many micro-sources located far away from each other (Pogaku et al., 2007). Although rated at much lower power, these grid-forming droop-based strategies can be extended to large power OWFs operating in islanded mode, *taking into account their characteristcs*, as demonstrated by Blasco-Gimenez et al. (2010).

3.1 Control Structure

According to the definition in Rocabert et al. (2012), grid-*forming* converters are controlled in closed loop to work as ideal AC voltage sources (low-output impedance), while grid-*feeding/following* converters are controlled as current sources with high parallel output impedance and can't operate in islanding/stand-alone mode as they require a grid-forming converter or local SG to set the bus voltage and frequency.

The control structure of grid-forming control consists of different functional blocks, as shown in figure 1. Since the main objective of grid forming control is to operate the PEC as an ideal AC voltage source of given amplitude V_o^* and frequency ω^*, it consists most importantly of a *voltage* control loop C_{V}. The short-comings of the *single-loop* approach, explained in Zeni et al. (2015), are already known from switch-mode power supplies and electrical machine drives as over-currents during transients & faults can not be limited due to the lack of an explicit closed-loop current controller. In addition, sensitivity to disturbances and plant-parameter fluctuations eliminates *open-loop* control as a good choice. The most commonly used alternative thus, is the *nested/cascaded* voltage-current controller (Zeni et al., 2015), in which a *faster* inner *current* control loop C_{I} is added. C_{I} is designed to have a relatively smaller time constant than C_{V}, for decoupling i.e. C_{I} behaves as an almost perfect current controller for the slower C_{V}. The controllers are in the synchronous reference frame that uses an angle θ^* (for $abc \rightleftharpoons dq$ transformation) obtained from the *synchronization* block (Green and Prodanović, 2007).

While grid-feeding converters require perfect synchronism with the AC voltage at the point of connection to accurately regulate the power exchange with the grid, in the case of grid-forming converters the synchronization system must provide precise signals for *both* islanded and grid-connected modes of operation. It works as a fixed frequency ω^* *oscillator* in the former case while slowly varies the phase-angle & frequency of the island voltage during the reconnection transient to resynchronize with the grid voltage, in the latter. The most extended method used is a Phase Locked Loop (PLL), also called *voltage-based* synchronization as the frequency and phase-angle of the grid voltage vector is used for control. However, enhancements are needed to ensure stability under unbalanced and distorted voltage conditions as voltage sag, weak grids or off-grid operation can lead to instabilities. Alterately, *power-based* synchronization can also be used for synchronization as the structure of the *swing equation* that governs synchronous machine (SM) dynamics, can be equated to that of a PLL, in the sense that the PLL structure can be modified to extract the derivative term of the frequency (inertia in SMs) and the speed variation (damping in SMs), as shown in van Wesenbeeck et al. (2009). This presents a more stable solution and allows the power controller to also act as the synchronization block.

The outer *power* control loops $C_{\mathrm{P}}, C_{\mathrm{Q}}$ are required to regulate the real P and reactive Q powers exchanged with the grid (in grid-connected mode) or meet the demand set by the load (in islanded mode), while ensuring communication-less real & reactive power sharing between the multiple paralleled inverters. The simplest method for this, by only relying on local measurements, is the *droop control* scheme, which was initially introduced for SGs in utility scale grids, and now is well incorporated into microgrids (Arbab-Zavar et al., 2019). The primary level of the *3-level hierarchical* control, explained in Guerrero et al. (2011), employs droop control equations 1 & 2, based on grid X/R ratio, to mimic the self-regulation capability of a grid-connected SG and allow power sharing in microgrids without using critical communication links (Rocabert et al., 2012).

$$\text{X»R: } \omega = \omega^* - k_{\mathrm{P}}^{\omega}(P - P^*) \text{ and } V = V^* - k_{\mathrm{Q}}^{V}(Q - Q^*) \tag{1}$$

$$\text{X«R: } \omega = \omega^* + k_{\mathrm{Q}}^{\omega}(Q - Q^*) \text{ and } V = V^* - k_{\mathrm{P}}^{V}(P - P^*) \tag{2}$$

Although easy to implement with high reliability and flexibility, traditional droop control suffers from an inherent tradeoff between load-sharing & voltage-regulation, load dependent frequency-deviation, slow dynamic response due to filters for P, Q and non-linear load-sharing issues due to harmonics. A variable *virtual impedance* Z_{V} can be used to add harmonic (f_{n}) droop characteristics and improve tradeoff between current harmonic sharing & voltage total harmonic distortion, by adjusting output impedance seen by harmonics and the fundamental. Additionally, this allows intelligent mode-switching with soft-start to take advantage of the fast converter response while avoiding large transients (Guerrero et al., 2011). Instead of the traditional P-f droop control, the swing equation governing SM dynamics with inertia and damping, can also be used to have a steady-state $\frac{\Delta P}{\Delta f}|_{\infty}$ droop characteristic, as shown by the equivalence of the two in D'Arco and Suul (2013). Finally, the swing equation controller, essentially a low pass filter, can be replaced by enhanced electromechanical controller dynamics (eg. detailed SM emulation, or PI & Lead-Lag (LL) controllers) to remove the inherent limitations of SMs and provide adjustable characteristics like independent tuning of inertia, damping & steady-state droop (using LL), or high non-linear behaviour during grid faults and connection/disconnection processes. However, in case of no steady-state droop (for PI) or damping-constrained droop (for swing equation), external *secondary* droops need to be added, like virtual governor droop R for real power sharing and virtual Automatic Voltage Regulator (AVR) for reactive power sharing between the paralleled PEC-interfaced WTs.

3.2 Control Strategies

In the last decade, many different control solutions have been proposed in literature to replicate the system-level functionalities of SGs like intertial & damping characteristics, frequency/voltage droop, self-organising parallel operation and automatic power sharing. The VIrtual Synchronous MAchine (VISMA) concept, introduced by Beck and Hesse (2007), uses a power-based synchronization method with a detailed implementation of the electro-mechanical model of a SM in its power control loop, thus eliminating the need for PLL and allowing conventional and proven grid operation with the usual static and dynamic properties that are characteristic to SMs, both desired *and undesired*. Since a virtual rotating mass is created which is electrically effective in relation to the grid, VISMA makes it possible to connect every kind of distributed micro-sources and renewables even to weak grids. Many improvements have been made based on the VISMA concept, as listed in D'Arco and Suul (2013), including Reduced order SM model for easier implementation and to avoid unnecessary details, Synchronverter (Zhong and Weiss, 2009) for mimicing only the *static* behaviour of SG using swing equation & reactive power control for the excitation voltage. Parallely, the Virtual Synchronous Generator (VSG) concept (van Wesenbeeck et al., 2009) emulates the swing equation by using the structure of PLL for power-synchronization. Additional enhancements include virtual impedance/admittance, damping correction loop, PLL removal (Qing-Chang Zhong et al., 2014), and virtual governor & AVR based loops. Recently, non-linear control based grid-forming strategies relying on duality between PEC & SM have been proposed like SM-matching (Arghir et al., 2018) and Virtual Oscillator Control (Johnson et al., 2017), that provide steady-state droop-like behaviour with a faster & better damped response during transients. The four grid-forming control strategies, that have been selected for this study, are explained ahead.

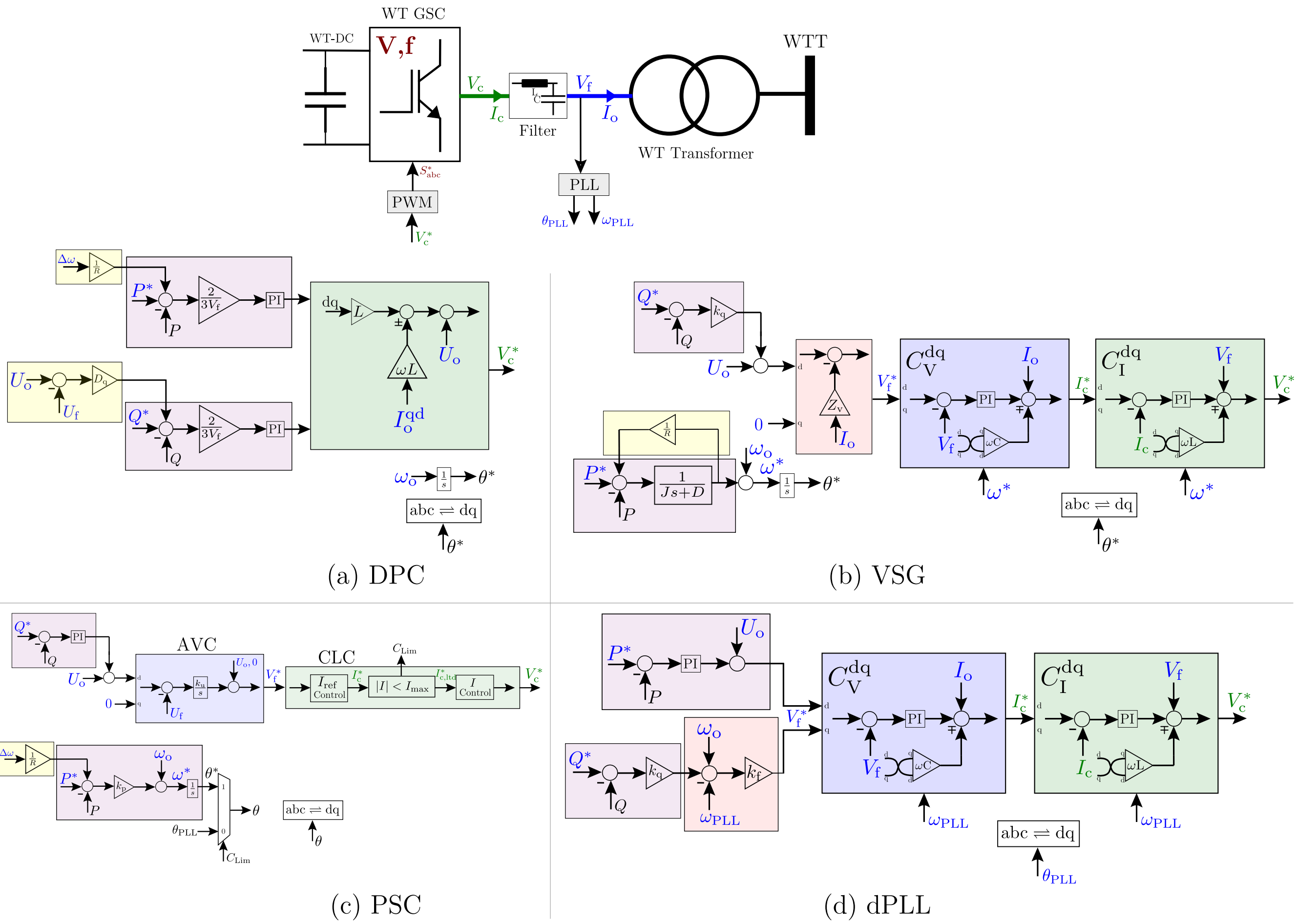

Figure 2. Control structure for (a) Direct Power Control (DPC), (b) Virtual Synchronous Generator (VSG), (c) Power Synchronous Control (PSC) and (d) Distributed-PLL based (dPLL) grid forming control strategies.

3.2.1 Virtual Synchronous Generator (VSG)

The VSG control structure implemented here is shown in figure 2(b), and is based on D'Arco et al. (2015). It uses standard cascaded voltage-current control with swing-equation (power-synchronization) for generating the frequency reference & synchronization angle and controlling real power. The reactive power controller based on Q-V droop is used to provide the voltage amplitude reference. Virtual impedance can also be added to reduce sensitivity to small grid disturbances by providing additional damping. Since a sufficiently high enough damping leads to a low inherent steady-state $\frac{\Delta P}{\Delta f}|_{\infty}$ droop, an external *secondary* virtual governor f-P droop is needed to mimic the traditional 3-5% SG speed droop characteristic.

3.2.2 Power Synchronous Control (PSC)

The PSC control structure, explained in Zhang et al. (2010), is shown in figure 2(c). Here also power synchronization is used just like in VSG, however unlike the swing equation where the power difference drives the rotor speed dynamics which is then changed to electrical angle i.e. double integration for P-θ transfer function (equation 3), the the PSC Loop (PSL) directly gets the phase angle by a single integration of the power difference, as given by the equation 4. Due to 1 less integrator, PSC has higher stability margin, however due to 0 inherent steady-state droop, outer droops are needed for paralleling multiple grid forming units. Moreover, no virtual inertia or damping is present due to absence of rotor dynamics.

$$P_{\mathrm{m}} - P_{\mathrm{e}} = J\omega\frac{\mathrm{d}\omega}{\mathrm{d}t}, \frac{\mathrm{d}\omega}{\mathrm{d}t} = \theta \Longleftarrow \text{Swing Equation} \tag{3}$$

$$J\frac{\mathrm{d}\Delta\theta}{\mathrm{d}t} = k_{\mathrm{P}}(P_{\mathrm{m}} - P_{\mathrm{e}}) \Longleftarrow \text{PSL} \tag{4}$$

For the AC Voltage Controller (AVC), an emulation of the exciter of a SM is used except that integral control is used instead of the traditional proportional control, to supress high-frequency disturbances. Analysis by Zhang et al. (2010) shows that the open loop $\frac{\Delta P(s)}{\Delta\theta(s)}$ transfer function has a right half plane (RHP) zero meaning extra time delay & *non-minimum phase system* type response. Additionally, the RHP zero moves closer to origin at higher converter-voltages & load-angles leading to lower bandwidth and lesser phase margin. Finally, grid-frequency resonant poles (for low resistance grids) are also present that need to be damped out, for which the voltage control is governed by equation 5, where $H_{\mathrm{HP}}(s)$ is a high-pass filter used for resonance damping, as it is effectively a virtual resistor at high frequencies. Lastly, a Current Limitation Controller (CLC), employing equations 7 & 8, is used, which in *normal* mode simplifies to equation 5, but in *fault* mode limits the current output of the converter to I_{max} and generates a selector signal C_{Lim} to disable the PSL and switch to conventional PLL-based synchronization. The PSC has demonstrated strong performance in weak networks.

$$\boldsymbol{v}_{\mathrm{C}}^{*} = V_0 - H_{\mathrm{HP}}(s)\mathbf{i}_{\mathrm{C}} \Longleftarrow \text{Voltage control} \tag{5}$$

$$H_{\mathrm{HP}}(s) = \frac{k_{\mathrm{v}}s}{s+\alpha_{\mathrm{v}}} \Longleftarrow \text{High pass filter} \tag{6}$$

$$\boldsymbol{i}_{\mathrm{C}}^{*} = \frac{1}{\alpha L_{\mathrm{C}}}[V_0 - \boldsymbol{v}_{\mathrm{F}} - j\omega L_{\mathrm{C}}\boldsymbol{i}_{\mathrm{C}} - H_{\mathrm{HP}}(s)\boldsymbol{i}_{\mathrm{C}}] + \boldsymbol{i}_{\mathrm{C}} \Longleftarrow \text{Current reference control} \tag{7}$$

$$\boldsymbol{v}_{\mathrm{C}}^{*} = \alpha L_{\mathrm{C}}(\boldsymbol{i}_{\mathrm{C}}^{*} - \boldsymbol{i}_{\mathrm{C}}) + j\omega L_{\mathrm{C}}\boldsymbol{i}_{\mathrm{C}} + \boldsymbol{v}_{\mathrm{F}} \Longleftarrow \text{Current control} \tag{8}$$

3.2.3 Distributed PLL-based (dPLL)

The dPLL control structure is based on Yu et al. (2018) and shown in figure 2(d). Originally developed for DRU-connected OWFs, the real power controller is used to generate the *d*-axis voltage reference as power flow is determined by offshore voltage, governed by equation 9, and a reactive power droop controller regulates frequency to share the DRU demanded Var. Instead of the conventional approach of setting the *q*-axis voltage reference to 0, since PLL output can be used as an indication of frequency deviation, a Frequency Control Loop characterized by equation 10, is embedded in the q-axis to use the output of the Q-f droop-controller.

$$V_{\mathrm{DC}} = 2\left(1.35V_{\mathrm{F}} - \frac{3}{\pi}XI_{\mathrm{DC}}\right) \tag{9}$$

$$V^{*}_{\mathrm{Fq}} = k_{\mathrm{f}}(f^{*} - f) \tag{10}$$

Yu et al. (2018) demonstrates frequency controllability with plug-and-play capability providing successful sequential start-up of the grid-forming WTs and automatic synchronization of the offline WTs during connection with minimal impact, to supply the Var required to energize transformers, filters and finally ramp up the offshore voltage and start delivering active power to onshore grid. However, only the start-up and synchronisation of an islanded OWF to an energized onshore synchronous power system via a DR-HVDC link is studied while the energisation of export cable and onshore converter, expected from a blackstart service provider, was not looked into.

3.2.4 Direct Power Control (DPC)

DPC was introduced by Noguchi et al. (1998) in which the instantaneous p & q are controlled without requiring AC voltage sensors, PLL or an inner current controller, by using a look-up table and hysteresis comparators on the power errors to select the optimum switching state of the converter. Since then it has undergone many enhancements to deliver improved performance like using space vector modulation for constant switching frequency, employing sliding mode control for robustness, model predictive control for the multivariable case, and grid voltage modulated DPC for good transient-response and steady-state performance in non-linear systems. The control structure shown in figure 2(a) is based on Gui et al. (2019), which derives a standard *dq*-axes current model from the well known *instantaneous pq theory* (Akagi et al., 2017) of the DPC model to eliminate the inner control loops.

4 Model Description

The schematic model of the system shown in figure 3 has been developed in PSCAD and is based on Sakamuri et al. (2019). It consists of a 400 MW grid-forming OWF connected to the onshore AC grid by means of a 200 km long 1200 MW ±320 kV symmetrical monopole point-to-point (P2P) HVDC link, as shown in figure 3(a).

A Detailed Equivalent Model (DEM) of the Half-Bridge Modular Multilevel Converters (MMC) is used for both terminals of the VSC-HVDC link, which represents each sub-module (SM) as an equivalent circuit model, stacks them up in series, simplifies the whole circuit, solves the network using this model, and then converts back to the equivalent SMs. This gives a fast solution along with information about what happens inside the SMs. The offshore terminal (T2) MMC is controlled in grid-following mode since the offshore AC network voltage is formed by the grid-forming OWF, so the converter regulates the HVDC link voltage V_{DC} and reactive power injection Q_2 into T2. At the onshore terminal (T1), the MMC is controlled in grid-forming mode to regulate the onshore AC voltage magnitude V_1 & frequency f_1, in the scope of the blackstart case study

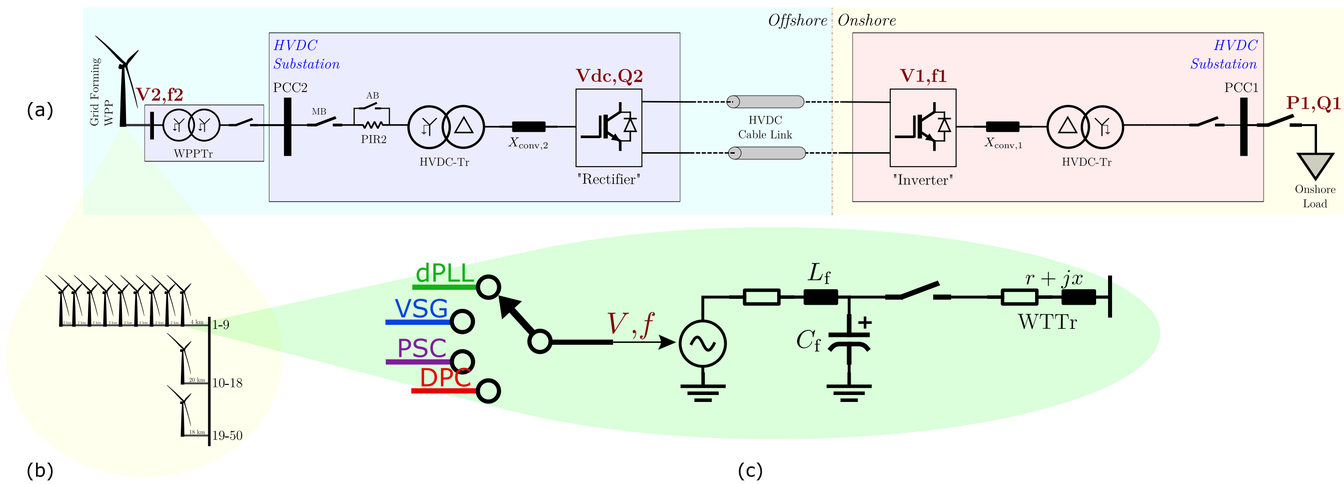

Figure 3. Schematic of the implemented PSCAD model of the system under study. This figure shows (a) the 2-Terminal P2P HVDC link, with grid-following offshore-MMC & grid-forming onshore-MMC (b) the partial aggregation used to model the OWF, and (c) the average model of the *grid-forming* WT-GSC implemented with 4 different control strategies operating in islanded mode.

performed in this paper. The MMC models used have standard HB-MMC inner control loops, such as cell voltage balancing and circulating current suppression, and the control structure for the V_{DC}-Q_2 (for T2) & V_1-f_1 (for T1) modes, can be seen in Sakamuri et al. (2019). Frequency dependent (phase) models in PSCAD are used for the HVDC export cable. The HVDC converter transformers models include magnetic characteristics such as saturation and inrush current. Finally, a Pre-Insertion Resistor (PIR) that is bypassed after a Pre-Insertion Time (PIT) by using coordinated Main & Auxilary Breakers (MB & AB), is used for limiting the transient magnetic-inrush current peak during hard-switching energization of the HVDC transformer.

The OWF consists of 50 Type-4 (fully-rated PEC interface) 8 MW WTs, as a *partially-aggregated* model shown in figure 3(b), based on Muljadi et al. (2008). It consists of 9 individual WT_{1-9} models on the first string, the second string with WT_{10-18} aggregated into a 72 MW WT model, and the remaining 32 WT_{19-50} aggregated into one 256 MW model. Coupled π-section models are used for the 66 kV array cables and magnetic detailed model (inrush & saturation) is used for the $66|155$ kV offshore WPP transformer. Lastly, the WT is modelled as a grid-forming unit operating in islanded mode, and so the Grid-Side Converter (GSC) is modelled as a voltage source (average model) controlled by the 4 different grid-forming strategies, viz. VSG, PSC, dPLL & DPC, that are explained in section 3.2. This is shown in figure 3(c).

4.1 Limitations & Assumptions

The model described above has certain limitations. Firstly, the WT Rotor-Side Converter (RSC) & changes to the turbine controller that are required for grid-forming operation, have not been modelled. In conventional grid-following operation of the WT, the RSC is controlled to extract maximum power from the generator while the GSC maintains power balance to control the DC link voltage of the back-to-back PEC interface of the WT and the reactive power output at the AC terminal.

Table 1. Energization Sequence

Stage	Time [s]	Events
1	0	WTs energized simultaneously and operate in grid-forming mode.
2	1.3	WPP begins offshore grid-forming at PCC-2 and
		MB is closed to insert PIR for energizing the offshore transformer and pre-charging the offshore MMC cells.
	1.6	PIR is bypassed after PIT (= 0.3s) by closing AB.
3	2.1	Offshore MMC is de-blocked to control the DC voltage; HVDC link is energized
4	2.5	(a) Controlled pre-charging of onshore MMC's upper arm cells with lower arm blocked.
	2.8	(b) Controlled pre-charging of onshore MMC's lower arm cells with upper arm blocked.
	3.1	(c) Controlled pre-charging of onshore MMC finished; both arms blocked.
5	3.3	Onshore MMC is de-blocked to control voltage & frequency; Onshore AC PCC-1 is energized.
6	4	Onshore 30 MW block load is connected.

However, in grid-forming mode, the GSC can not control the DC link & reactive power anymore and the required generator torque & real power is set by the AC-load, not the turbine controller, which now has to regulate the speed using the pitch controller (and especially avoid overspeeding during low AC-load & high winds). Hence, the RSC control requires changes to be able to maintain the DC link voltage constant by ensuring real power balance (Pérez et al., 2019). Since the WT rotor & DC-link dynamics are outside the scope of this study, the model assumes a constant WT-DC link voltage. Additionally, since an average voltage source model of the GSC is used for the purpose of reducing simulation time, switching transients and their related issues like voltage surges or TOVs are not modelled. Moreover, the WT transformer is modelled as a pure electrical impedance $r + jx$ without any magnetic characteristics as it can be *soft-started* along with the WT voltage ramp-up, to avoid magnetic inrush & saturation effects. Secondly, for this study, although power sharing between the WTs inside the WPP has been controlled by including the outer power control loops, the WTs are started-up *simultaneously* as opposed to a more realistic *sequential* energization (eg. Yu et al. (2018)), as the study mainly focuses on the capabilities of the grid-forming OWF to provide blackstart services to the onshore grid while dealing with offshore network transients due to energization of the large converter transformer, HVDC converters and export cable, in a controlled manner. This puts any synchronization dynamics of multiple grid-forming PEC interfaced WTs out of the scope of this study. Additionally, substation load has not been modelled here because it is negligible with respect to onshore load.

5 Simulation Results

In this section, the results of the dynamic simulations performed in PSCAD are presented. The energization sequence, events of which are described in detail in table 1, is based on Sakamuri et al. (2019), but includes an extra stage of *DC-side controlled pre-charging* of the onshore MMC cells and the outer $C_{\mathrm{P,Q}}$ control loops for real & reactive power sharing amongst the WTs

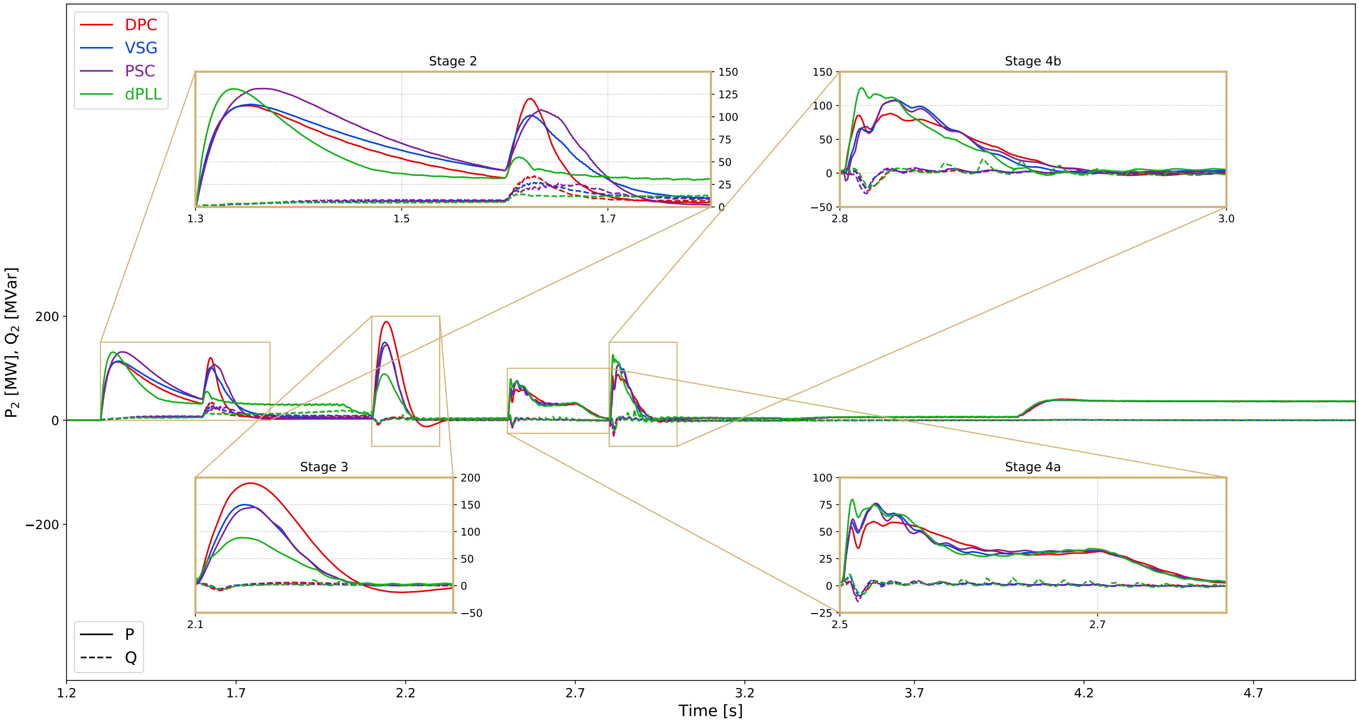

Figure 4. Real (solid line) & reactive (dotted line) power outpu of the offshore WPP with zoomed insets to show transients in selected stages of the energization sequence.

inside the WPP. The entire sequence is simulated, however the main focus is on testing the characteristics of the different control strategies in enabling the OWF to deal with the energization transients and so we focus on the real & reactive power outputs of the WPP, and with the voltage & frequency at the offshore PCC-2. *Hard-switching* is used here despite the advantages of *soft-start* energization, as the former is more demanding on the grid-forming OWF in terms of the transients (eg. TOV, oscillations) linked to energization of transformer, cable and HVDC link.

Figure 4 shows the waveforms for the real & reactive power outputs of the WPP during the different stages of the energization sequence. Since the grid-forming offshore WPP is operating in islanded mode, the real & reactive power demand is set by the load, which depends on the particular stage of energization. For stage 2, it is the Var required for magnetic energization of the offshore transformer and *AC-side* pre-charging of the offshore MMC cells. A PIR is inserted for PIT to limit the inrush peak. In stage 3, power is required to energize the HVDC cable when the offshore MMC is de-blocked to control the HVDC link voltage, while in stage 4, the *DC-side* pre-charging of the onshore MMC cells draws power from the OWF to maintain the energy balance on the HVDC link. Finally, the OWF supplies power to match the onshore block load in stage 6. Since the scope of this study is to focus on the offshore wind farm behaviour as a voltage source during the different stages of energization, the waveforms for the voltage & frequency at the offshore PCC-2 are presented in figures 5 & 6, respectively.

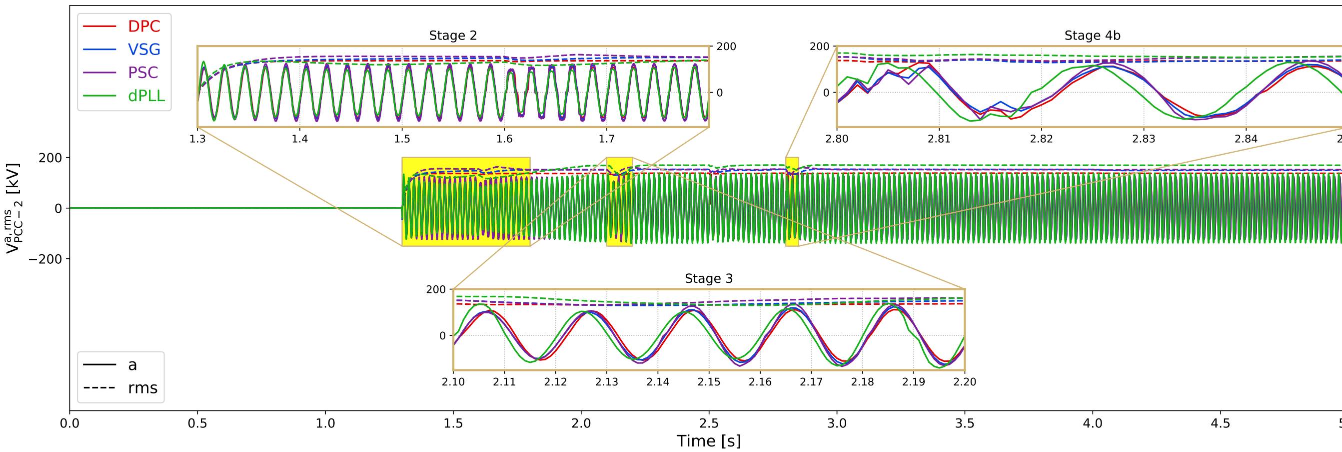

Figure 5. Voltage at offshore PCC-2 with zoomed insets to show transients in selected stages of the energization sequence.

The grid-forming WPP, controlled as a voltage source, has different characteristics based on the control method used. DPC is the most straightforward control technique with *direct* voltage and frequency control, without any inner loops, and doesn't have any electro-mechanical characteristics like inertia or damping. Thus it has the highest frequency swing, as can be seen from figure 6, along with highest transient peaks visible in the zoomed insets of the power waveform in figure 4, mainly stages 2 & 3. Comparatively, VSG has a lower frequency dip due to inertia emulation in its power controller, along with lower transient power peaks due to damping provided by virtual impedance. On the other hand, PSC has a higher frequency swing than VSG due to absence of inertia emulation, but the damping provided by $H_{\mathrm{HP}}(s)$ in the AVC reduces the transient power peak compared to DPC, visible in stages 2 & 3 of figure 4. However, the RHP zero in the PSC leads to an inherent delay that can be seen especially, from the shifted frequency nadir after the 2.8s event in stage 4 of figure 6 and the shifted power peak after the 1.6s event in stage 2 of figure 4. Additionally, the non-minimum phase system type behaviour of the PSC due to its RHP zero is also evident from the frequency rise as opposed to dip for other 3 methods, at the 1.6s event in stage 2 of figure 6. Contrary to the *power-synchronization based* VSG & PSC methods, the frequency swing in dPLL is lowest in all stages 2-6 with no overshoot in stage 1, as is clear from the figure 6, due to the frequency controllability of the *PLL-based* frequency control loop, which also provides damping and reduces the transient power peak, seen especially after the 1.6s event in stage 2 and stage 3 in fgure 4. However, after the 1.3s event in stage 2 in figure 4 the transient power peak for dPLL is higest during energization of the transformer with a PIR. This is because the dPLL is a voltage source controlled with Q-f, P-V coupling which not only leads to a drop in frequency when Var is demanded by the magnetic reactance of the transformer, but also causes a significantly higher distortion in voltage, compared to the other 3 methods, as shown in stage 2 of figure 5, due to the PIR reducing the decoupling, to which the dPLL controlled WPP reacts with a surge in power output.

It is clear from the PQ waveforms shown in figure 4 that there are some differences in the transient behaviour of the 4 control strategies, despite having an overall similar profile. The zoomed insets for the different stages in the V waveform in figure 5 show that the OWF with the 4 different grid-forming controls can successfully energize the transformer, cables &

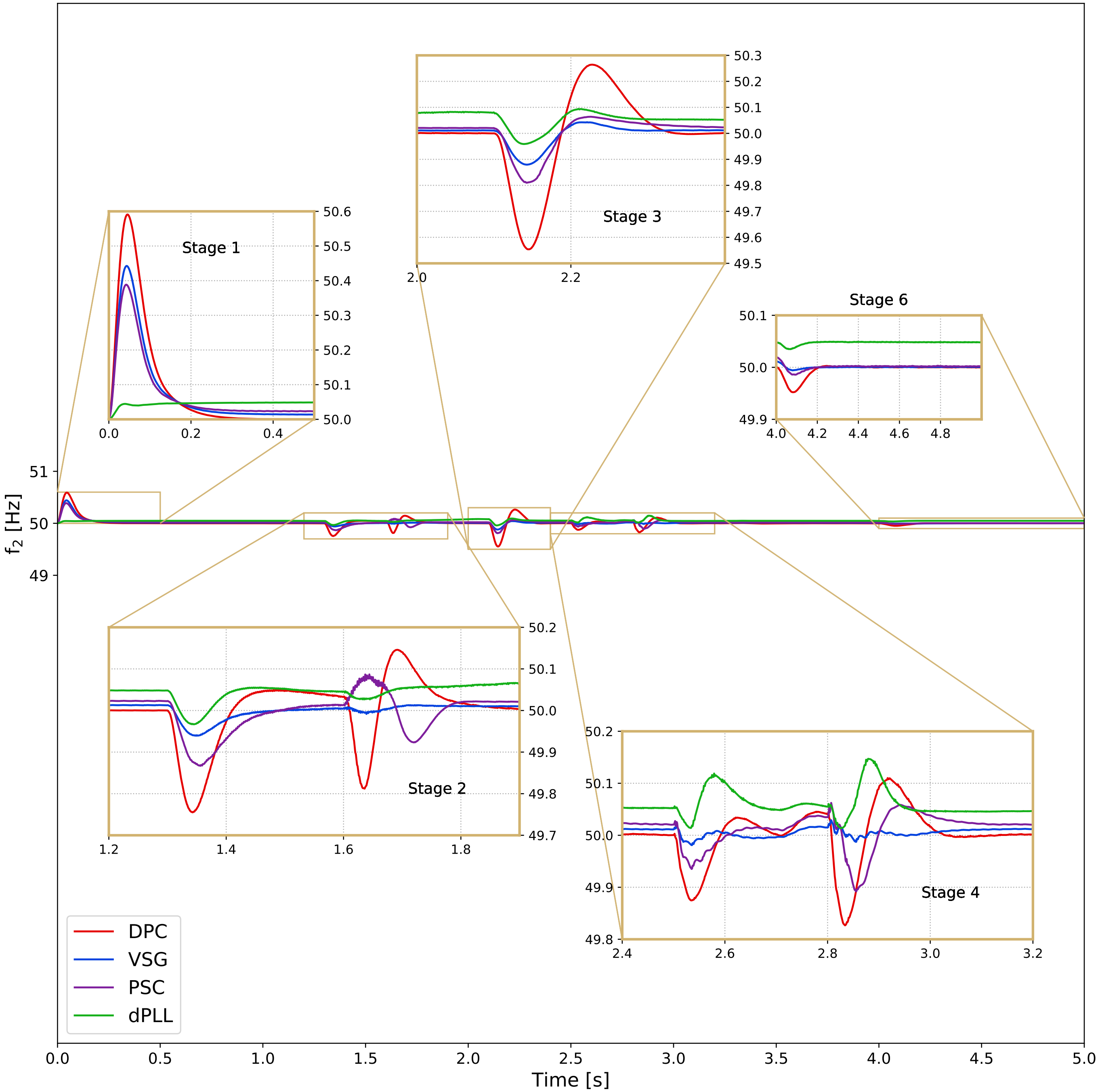

Figure 6. Frequency at offshore PCC-2 with zoomed insets to show transients in the different stages of the energization sequence.

Table 2. Summary of the differences in transient behaviour of the different grid-forming control methods; + good (low amplitude), − bad (high amplitude).

Control	Frequency Swing	Power Peak	Remark
DPC	−	−	No electro-mechanical characteristics
PSC	−	−	Non-minimum phase, RHP zero
VSG	+	+	Inertia, Damping, Inherent droop
dPLL	++	++	PLL-enhanced frequency control

MMC cells and supply the onshore load, while maintaining a stable voltage at the offshore PCC-2, with only minor distortions during stages 2-4 that are recovered fast by the grid-forming controls. However, significant difference difference can be seen in the frequency transients in figure 6 which also demonstrates the characteristics of the different control methods. This is summarized in table 2.

6 Conclusions

Recent tests on HVDC interconnectors like SK-4 and NEMO link have shown that VSC-HVDC can be used for blackstart services in a *top-down* restoration strategy. This makes VSC-HVDC connected offshore wind farms promising candidates for providing blackstart and islanding operation capabilities, as the conventional large thermal power plants are being phased out and wind farms grow bigger, to meet the decarbonization aims. This paper presents an overview of the different strategies for the participation of offshore wind in a traditional *bottom-up* power system restoration procedure and focuses on *grid-forming* as the main control change required to enable blackstart and islanding services from wind turbines, facilitate their earlier participation and minimize the dependence on auxiliary diesel generators. The overall structure of grid forming control has been explained with the constituent functional blocks, along with conceptual explanation of 4 different techniques viz. VSG, PSC, dPLL and DPC. These methods were then tested in a study of the blackstart of onshore load by an HVDC-connected offshore wind farm, focusing on transients due to energization of transformers, cables, MMC cells and HVDC link. The simulation results demonstrate that all the 4 methods are able to deal with the energization transients in a controlled manner while maintaining stability of voltage and frequency at the offshore terminal. However, differences in their transient behaviours were observed and are summarised in table 2. The DPC & PSC have high frequency swing & transient power peaks, with the latter additionally having non-minimum phase behaviour. Contrarily, VSG & dPLL show superior performance but need further investigation, especially in regards to offshore & harmonic load sharing, synchronization transients during sequential energization of wind turbines inside the wind farm, and the effect of blackstart and islanded operation on rotor & turbine DC link dynamics, before wind turbines can be deemed blackstart-*able*.

Code and data availability. Inquiries about and requests for access to the simulation models used in this study should be directed to the authors.

Appendix A: Parameters

Table A1. Main circuit parameters of the model [T2 - offshore, T1 - onshore, X_L - leakage reactance].

Parameters	**Values**
WT rating	8 MW, 66 kV
WT GSC Filter	$L_\mathrm{f} = 10\%$, $C_\mathrm{f} = 5\%$
WT transformer	$R = 1\%$, $X_\mathrm{L} = 1\%$
WPP rating	400 MW
WPP transformer	$66\|155$ kV, $X_\mathrm{L} = 12\%$
HVDC transformers	1000 MVA, $X_\mathrm{L} = 15\%$
	T2: $155\|390$ kV, T1: $390\|400$ kV
PIR, PIT	120 Ω, 0.3 s
HVDC link rating	±320 kV, 1200 MW, 200 km
MMC DEM	1000 MVA, 225 submodules per arm
Onshore load	30 MW

Author contributions. JS designed the simulation for the case study. AJ and JS implemented the models and carried out the simulations. JS and NC analysed the results. AJ prepared the manuscript with contributions from JS and NC.

Competing interests. The authors declare that no competing interests are present.

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